

Strength of Welded Pipe-plate Joints

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Abstract

The distribution of stresses of the welded pipe-plate joints is complicated. To study the strength of the joints, the parameter analyses were undertaken using nonlinear finite element method and uniform design approach. The pipe diameter, thickness, the plate width, height, and thickness were considered. Three kinds of loading conditions on the plate-the axial force, the moment, the combined axial force and moment were analyzed. The strength formulas of the joints are proposed by regression analysis. The verification tests demonstrate the reliability of the formulas.

Keywords

Strength; Welded Pipe-plate Joint; Parameter Analyses; Uniform Design

Introduction

The welded pipe-plate joints are usually presented themselves in the Vierendeel trusses for their simple configuration, easy and low-cost fabrication. The members of Vierendeel trusses are typical beam elements, suffering axial force, bending moment, and shear simultaneously [Wardenier 1982].

Joint stiffness has a great effect on the mechanical properties of the hollow steel section structures (HSS) [Syam 1996, Zhao 2000]. In the studies on the strength of HSS joints, yield line method, nonlinear finite element method, and joint model tests are frequently adopted. It is quite difficult to obtain the solutions to the joint strength using analytical theory for its complicate distribution of stresses. Nowadays, joint model tests are widely used in the studies [Zhao 1991]. Nonlinear finite element numerical simulation to the joints is another effective method [Packer 1997, Zhao 2000].

By now, there are no literatures on the strength of the welded pipe-plate Vierendeel truss joints. The purpose of the paper is to highlight the strength formulas of the joints.

Joint Parameters

The strength of the welded pipe-plate joints is affected

by many factors, such as the pipe diameter and thickness, the plate width, height and thickness (Fig. 1). The analysis on the strength of the joints needs many models with different dimensions. Uniform design method is suitable for the design of experiments with multi-variables. By regression to the experimental data, the relationship between computation objective values and factors can be obtained.

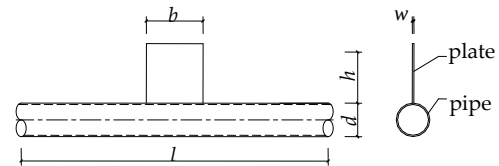


FIG. 1 JOINT OF PIPE-PLATE VIERENDEEL TRUSSES

For a uniform design with s factors, q levers for each factor, the observation points are:

$$P_n(k) = (ka_1, ka_2, \dots, ka_s) \pmod{q} \quad (1)$$

where $k=1, 2, \dots, q$; and $a_1, a_2, \dots, a_s$ are natural numbers. If q is a prime number, the observation points are:

$$P_q(k) = (k, ka, ka^2, \dots, ka^{s-1}) \pmod{q} \quad (2)$$

where a is a natural number.

In the study, the pipe length l is fixed to be 1.2 m. Factors are the pipe diameter d , thickness t , the plate height h , width b , and thickness w . By referring to d respectively, the four experimental factors are derived: the pipe diameter to thickness ratio β , the pipe diameter to plate width ratio τ , the plate height to width ratio γ , the plate width to thickness α . Three kinds of loading conditions on the plate- the axial force N , the moment M , the composed loading of N and M are considered. The plate bending moment M is defined as follows.

$$M = Qh \quad (3)$$

where Q is the shear force at the inflection point on the plate branch. The combination of N and M is controlled by the variable ζ . The formulas of the

experimental factors are given as follows.

$$\left\{\begin{array}{l}\beta = d / t \\ \tau = b / d \\ \gamma = h / b \\ \alpha = b / w \\ \zeta = \tan ^{-1}\left(N / N_{\max }\right)\end{array}\right. \quad (4)$$

Each factor is divided into five levels separately. β =20, 40, 60, 80, 60; τ =0.3, 0.85, 1.4, 1.95, 2.5; γ =1, 2, 3, 4, 5; α =10, 21.25, 32.5, 43.75, 55; ζ =9, 27, 45, 63, 81. Model materials use Chinese standard steel Q235. Uniform design table $U_{30}(6^5)$ is used to determine the combination of the factors (Table 1).

TABLE 1 COMBINATION OF FACTORS						
No.	Combination of Factors					
	$d(\text{m})$	β	τ	γ	α	ζ
1	0.21	60	0.85	22.5	2	10
2	0.13	20	2.5	47.5	4	32.5
3	0.21	40	1.4	10	4	55
4	0.13	100	1.4	60	1	43.75
5	0.21	80	0.85	47.5	3	43.75
6	0.09	80	0.85	60	4	10
7	0.05	40	1.4	47.5	1	10
8	0.13	60	2.5	10	3	21.25
9	0.05	40	1.95	22.5	3	32.5
10	0.09	100	1.4	35	5	55
11	0.17	40	0.3	35	5	43.75
12	0.05	60	2.5	60	5	43.75
13	0.09	100	2.5	35	2	10
14	0.05	100	0.85	22.5	4	32.5
15	0.17	80	1.95	22.5	1	43.75
16	0.17	100	0.3	10	2	32.5
17	0.09	20	0.3	22.5	5	21.25
18	0.17	40	1.95	60	2	21.25
19	0.13	80	0.3	47.5	1	21.25
20	0.09	40	1.95	47.5	2	55
21	0.13	60	1.95	10	5	10
22	0.13	20	0.85	60	3	55
23	0.09	20	0.85	10	1	43.75
24	0.17	20	1.4	35	4	10
25	0.05	80	1.4	10	3	21.25
26	0.05	60	0.3	35	2	55
27	0.21	100	1.95	47.5	5	21.25
28	0.21	20	2.5	35	1	32.5
29	0.21	60	0.3	60	3	32.5
30	0.17	80	2.5	22.5	4	55

It is noted that some models may not match the actual structures. This is a drawback of uniform design method. In the arrangement of model design, it is remembered to keep the tests as actual as possible.

Computer Numerical Tests and Analysis

Newton–Raphson iteration procedure and arc length method are utilized to solve ultimate load-carrying capacity of the joints. Fig. 2 shows the typical curves of

the load to joint maximum displacement $w_{\max}$. According to the curves, the ultimate strength is determined for each test.

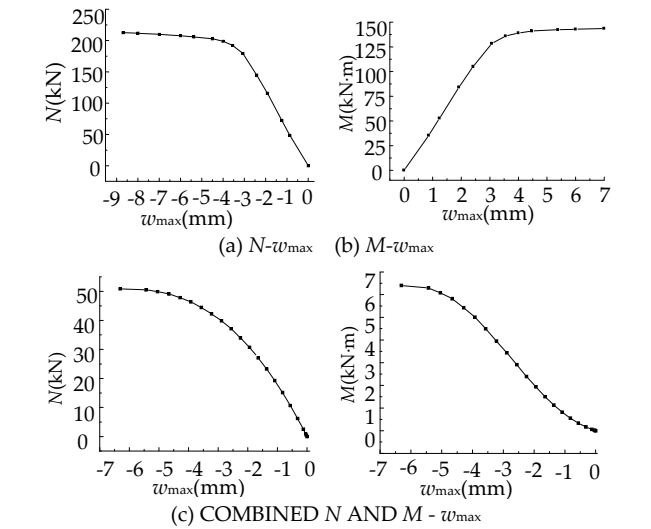


FIG. 2 TYPICAL CURVES OF LOAD TO $w_{\max}$

The results of numerical tests are shown in Table 2. Analyzing the test data, we can obtain the regression formulas of the joint strength.

TABLE 2 RESULTS OF COMPUTER NUMERICAL TESTS				
No.	$N_{\max}$ (kN)	$M_{\max}$ (kN·m)	Combined N and M	
			N (kN)	M (kN·m)
1	24.10425	101.1	24.08475	3.814543
2	15.2355	46.13	15.21225	2.409316
3	5.34285	14.96	4.2315	8.304784
4	2.08335	15.01	2.08275	0.329866
5	2.50395	9.4	2.2572	4.430003
6	1.156575	6.08	1.1502	0.586061
7	7.8105	35.34	7.401975	7.401975
8	3.5379	21.26	2.655975	16.76916
9	0.986475	3.62	0.9858	0.156131
10	0.1293225	0.47	0.12513	0.12513
11	4.151925	9.94	4.1391	0.655551
12	0.1678125	0.61	0.149258	0.292934
13	0.4734825	1.55	0.432353	0.848539
14	0.100335	0.4	0.053174	0.335724
15	5.7942	38.91	4.355775	27.50127
16	2.48865	10.02	2.41875	2.41875
17	9.606	23.08	6.9108	13.56321
18	22.62075	125.57	22.50075	11.46481
19	8.10825	37.51	7.569	14.855
20	2.928	10.92	1.44705	9.136312
21	1.511775	7.13	1.3398	1.3398
22	19.257	49.7	17.5365	17.5365
23	75.195	322.73	74.5005	37.96024
24	88.44	354.24	46.94325	296.3879
25	0.3756075	1.96	0.375578	0.059484
26	0.737445	2.02	0.719573	0.366644
27	1.4247	8.49	1.42125	0.72417
28	279.015	1380.9	271.335	271.335
29	6.510825	19.22	2.583375	16.31078
30	1.02	4.59	1.017075	0.51823

(1) the maximum axial force

$$N_{\max} = 325.7322 + 193.6124d - 11.1819\beta + 5.4516\tau - 70.7218\gamma + 0.1469\alpha + 627.3354d^2 + 0.1410\beta^2 - 4.9389\tau^2 + 9.0574\gamma^2 - 0.0104\alpha^2 \quad (5)$$

(2) the maximum moment

$$M_{\max} = -703.4120 + 911.1434d + 38.4485\beta + 134.6730\tau + 68.3785\gamma - 1.2233\alpha - 760.5800d^2 - 0.6875\beta^2 - 28.7190\tau^2 + 8.7415\gamma^2 - 0.0113\alpha^2 \quad (6)$$

(3) the combined axial force and moment

$$N = 312.0530 + 187.1513d - 10.6427\beta + 7.5211\tau - 69.3431\gamma + 0.1578\alpha + 608.1539d^2 + 0.1329\beta^2 - 5.4059\tau^2 + 8.8973\gamma^2 - 0.0104\alpha^2 \quad (7.1)$$

$$M = 20.9227 - 41.0636d + 0.9393\beta + 42.0712\tau - 10.8396\gamma - 2.1162\alpha + 1550.9460d^2 - 0.0313\beta^2 - 13.0197\tau^2 + 1.9147\gamma^2 + 0.02584\alpha^2 \quad (7.2)$$

Table 3 shows the basic data of the regression statistics.

TABLE 3 BASIC DATA OF THE REGRESSION STATISTICS

	$N_{\max}$	$M_{\max}$	N and M combined	
			N	M
Full Correlation Coefficient	0.9441	0.8753	0.9420	0.8430
Standard Error	6.1834	0.5695	6.0467	0.4923
Significant Sequence of the Former Six Variable	$d, d2, \beta, \gamma, \tau, \tau2$	$d, d2, \tau, \beta, \tau2, \gamma2$	$d2, d, \gamma, \beta, \gamma2, \tau$	$d2, \tau, d, \tau2, \gamma, \gamma2$

When $d=0.21$ and $\alpha=32.5$, the relationships between $N_{\max}$ and other factors are shown in Fig. 3. For $\gamma=3$, when τ is constant, $N_{\max}$ decreases with the increment of β ; when β is constant, $N_{\max}$ decreases with the increment of τ . For $\tau=1.4$, when β is constant, $N_{\max}$ decreases with the increment of γ first, and then increases with the rise of γ . When $d=0.05$ and $\alpha=32.5$, the relationships between $M_{\max}$ and other factors are shown in Fig. 4. For $\gamma=3$, when τ is constant, $M_{\max}$ decreases with the increment of β at first, and then increases with the rise of β ; when β is constant, $M_{\max}$ increases with the rise of τ . For $\tau=1.4$, when β is constant, $M_{\max}$ increases with the rise of γ ; when τ is constant, $M_{\max}$ increases with the rise of β at first, and then decreases with the increment of β .

The distribution points of combined $N/N_{\max}$ and $M/M_{\max}$ are shown in Fig. 5. From the engineering design views, the Eq. (8) is safety in the design of the

pipe-plate Vierendeel truss joints.

$$\frac{N}{N_{\max}} + \frac{M}{M_{\max}} \leq 1 \quad (8)$$

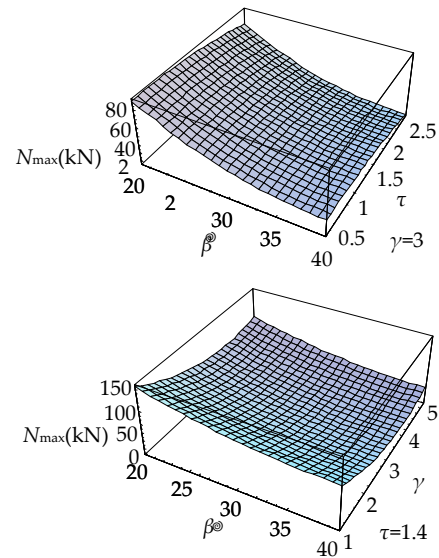


FIG. 3 RELATIONSHIPS BETWEEN $N_{\max}$ AND OTHER PARAMETERS WHEN $d=0.21$ AND $\alpha=32.5$

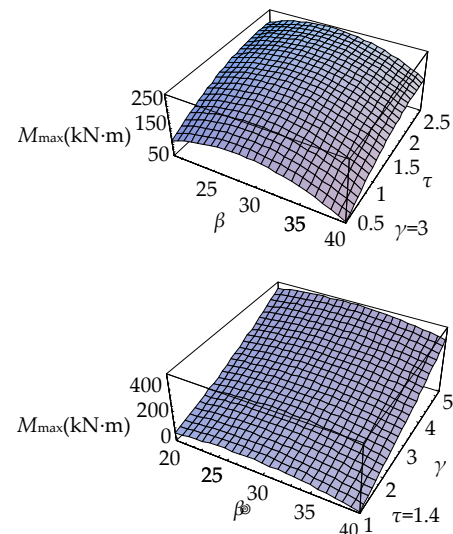


FIG. 4 RELATIONSHIPS BETWEEN $M_{\max}$ AND OTHER PARAMETERS WHEN $d=0.05$ AND $\alpha=32.5$

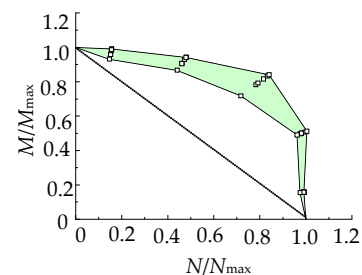


FIG. 5 DISTRIBUTION POINTS OF COMBINED $N/N_{\max}$ AND $M/M_{\max}$

TABLE 4 PART OF RESULTS OF VERIFICATION TESTS

No.	Combination of Factors						$N_{\max}$ (kN)		$M_{\max}$ (kN·m)		Combined N and M		
	d (mm)	β	τ	γ	α	ζ					N (kN)		M (kN·m)
							Actual	Formula	Actual	Formula	Actual	Actual	Formula
1	0.21	40	1.95	3	43.75	63	11.3805	11.6195	49.5082	50.1603	11.0303	26.5947	27.4172
2	0.13	20	1.95	4	10	45	61.1625	61.4698	251.3148	256.5924	59.3385	60.1692	60.8913
3	0.13	20	2.5	3	55	81	13.9808	14.2661	38.2583	38.7622	13.008	80.076	80.9649
4	0.05	30	1.4	3	10	45	5.6371	5.7555	5.5421	5.5981	5.4646	1.1476	1.1717
5	0.17	20	0.3	4	43.75	45	45.5003	46.0995	22.3288	22.7845	40.752	8.3134	8.3974
6	0.09	40	0.85	2	43.75	27	3.8855	4.0056	2.0109	2.035	3.7079	0.2891	0.2929
7	0.13	35	0.3	5	21.25	9	4.7947	4.6796	2.3492	2.3563	4.3487	0.1343	0.1347
8	0.09	40	2.5	5	32.5	63	1.5418	1.5603	6.3744	6.2311	1.5038	3.3202	3.3268
9	0.21	30	1.4	5	10	63	45.8318	50.0941	302.2945	305.65	45.0225	129.8916	131.6024
10	0.21	35	0.3	2	32.5	45	53.733	54.8077	21.6339	22.303	50.8433	6.4063	6.537
11	0.13	30	0.3	3	32.5	81	15.3555	15.0544	4.9075	4.9173	14.121	10.4313	10.2018
12	0.17	35	1.95	5	55	27	3.3245	3.3614	15.0368	15.2037	3.0857	2.606	2.6138
13	0.05	35	0.3	4	55	63	0.7631	0.7474	0.1124	0.1136	0.6877	0.081	0.082
14	0.05	20	0.85	5	32.5	27	1.4611	1.464	0.7484	0.7319	1.3088	0.1417	0.1385
15	0.05	25	2.5	2	55	45	2.5328	2.6088	2.109	2.1153	2.4087	0.6022	0.6145
16	0.17	40	0.85	4	10	81	19.476	19.5346	52.3451	51.1935	19.0725	69.6022	71.7548
17	0.05	40	1.4	3	21.25	9	1.5048	1.52	1.2555	1.2812	1.4723	0.049	0.0495
18	0.09	20	0.85	2	21.25	63	32.1068	31.4004	16.6525	16.2781	30.633	9.1985	8.9916
19	130	40	1.4	1	55	45	17.66925	17.4749	15.4627	15.5092	17.331	3.1542	3.2205
20	130	30	2.5	1	32.5	27	44.09775	43.1063	78.1853	76.3088	43.4663	7.1979	7.3418

Verification

To check the reliability of the formulas of the welded pipe-plate joint strength (from Eq. 5 to Eq. 8), another set of computation tests is made. Table 4 shows part of the results of the verification tests, and illustrates that the formula values are very close to the actual results.

Conclusions

The strength formulas of welded pipe-plate joints under three kinds of loading conditions on the plate-the axial force, the moment, and the combined axial force and moment are proposed by uniform design approach. The full correlation coefficients obtained from regression statistics are high comparatively. The verification tests demonstrate the reliability of the formulas.

The pipe diameter is the most significant factor in the joint strength. The pipe thickness, plate height and width are also significant to the joint strength.

From the engineering design views, the linear combination equation of the axial force-the maximum axial force ratio and the bending moment-the maximum bending moment ratio is safety in the design of the pipe-plate Vierendeel truss joints.

ACKNOWLEDGMENT

The support of Guizhou Province Natural Foundation of Education Department (2012-045) is gratefully acknowledged.

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